

A Scalable, All-Weather Energy-Managing Textile Synergizing Active Energy Harvesting and Passive Cooling

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Abstract

Current sustainable outdoor energy systems for energy harvesting and thermal management typically operate in isolation, leading to structural redundancy and suboptimal material efficiency. Integrating these complementary functions into a unified, scalable platform remains a key challenge. Here, we present a hierarchical energy-managing textile (EM-textile) that synergistically combines raindrop-energy harvesting with passive daytime radiative cooling (PDRC) for continuous, all-weather operation. Manufactured via a scalable process, the EM-textile integrates programmable electrodes with rationally designed composite layers. Its optimized photonic structure enables high solar reflectivity (93.3%) and mid-infrared emissivity (94.0%), delivering a sub-ambient cooling drop of 4–5 °C under solar irradiation of 965 W/m². Concurrently, the tailored electrode architecture enables a high raindrop-impact peak power density of 1.042 W/cm², capable of powering 44 LEDs from a single droplet. Field experiments demonstrate exceptional durability, multi-functional stability, and reduction in daily heating, ventilation, and air conditioning (HVAC) energy consumption. By unifying active energy harvesting and passive thermal regulation within a flexible, compliant format, this work provides a scalable pathway towards energy-autonomous smart buildings and wearable technologies.

1. Introduction

The urgent transition toward sustainable energy solutions has highlighted the critical role of green technologies, particularly in energy recovery and conservation systems^{1, 2, 3, 4, 5}. Among these, raindrop energy harvesting has emerged as a promising avenue for exploiting low-grade yet abundant renewable energy sources^{6, 7, 8, 9, 10, 11, 12}, given that approximately one-third of global regions experience annual precipitation (Fig. 1a)¹³. Droplet electricity generators (DEGs) have demonstrated particular promise, outperforming conventional raindrop energy harvesting technologies in capturing dispersed mechanical energy from raindrops since the discrete and low-frequency mechanical energy can be converted into electricity effectively by DEGs utilizing the triboelectric effect and electrostatic induction^{14, 15, 16}. Recent breakthroughs, such as the droplet-based electricity generator proposed by Xu et al., have further enhanced raindrop-generated instantaneous peak power output by three orders of magnitude through engineering surface charge density (SCD) gradients^{17, 18}. However, the practical deployment of these systems remains constrained by their reliance on climatic conditions and limited adaptability to diverse environments.

To address these limitations, researchers have explored synergies between raindrop harvesting and existing renewable technologies (e.g., photovoltaics^{14, 19, 20, 21, 22}, wind turbines^{16, 23}). Yet, a critical gap persists in integrating such systems with passive energy-saving strategies, a cornerstone of sustainable development. Passive daytime radiative cooling (PDRC) exemplifies this potential: by reflecting solar irradiation (0.3–2.5 μm) and emitting heat via the atmospheric transparency window (ATSW, 8–13 μm), PDRC achieves zero-energy cooling, significantly reducing building heating, ventilation, and air conditioning (HVAC) energy consumption. However, integrating DEG with PDRC remains challenging

because the two technologies impose distinct and sometimes conflicting material requirements. DEG typically relies on conductive and hydrophilic interfaces for efficient charge generation and collection, whereas PDRC requires highly reflective and infrared-emissive surfaces to achieve passive cooling. Developing a unified architecture that simultaneously enables efficient rain energy harvesting, strong radiative cooling, mechanical flexibility, and scalable fabrication represents a critical scientific challenge^{24, 25, 26, 27, 28}. In urban areas, where buildings account for substantial energy use⁴, combining energy harvesting from raindrops with PDRC could unlock dual benefits: energy generation and conservation (Fig. 1a). For instance, Singapore's annual precipitation holds 5.82 MJ of harvestable energy, while its building cooling demand reaches 641.13 GJ^{29, 30}. Pioneering work by Lee et al.³¹ demonstrated a hybrid DEG-PDRC glass window, yet scalable and flexible solutions, particularly for outdoor scenarios, remain underexplored. However, existing hybrid solutions (e.g., rigid glass-based designs³¹) remain in demand for lightweight, flexible, and scalable platforms that can adapt to dynamic outdoor environments, which is an indispensable requirement for real-world applications.

Here, we propose a hierarchical energy management textile (EM-textile) that synergizes raindrop energy harvesting with radiative cooling, through the structural integration of programmable electrode textiles and composite PDRC layers, enabling all-weather operation (Fig. 1b). Textile, as a universal interface material in outdoor scenarios (e.g., awnings, tents, clothing), offers inherent advantages: (1) high surface area that is directly proportional to the efficiency of energy capture, (2) mechanical flexibility to conform to uneven surfaces, and (3) compatibility with scalable manufacturing processes. By integrating programmable electrode textiles with poly(vinylidene fluoride-co-hexafluoropropylene)/expanded polytetrafluoroethylene (PVDF-HFP/ePTFE) composite layers, the EM-textile achieves 93.3% solar reflectivity and 94.0% mid-infrared (8–13 μm) emissivity, while an optimized electrode pattern minimizes signal interference from overlapping raindrops. This design not only attains a power density of 1.042 W/cm^2 under rainfall but also sustains a sub-ambient temperature of 4–5 $^{\circ}\text{C}$ under 965 W/m^2 solar irradiation. Field tests validate its dual functionality, bridging the gap between energy generation and conservation. Beyond laboratory metrics, this work establishes a framework for textile-based energy ecosystems, harmonizing active harvesting and passive conservation for sustainable cities and wearable applications.

2. Results and Discussion

The hierarchical design of the EM-textile integrates programmable textile electrodes with a hydrophobic ePTFE triboelectric layer and PVDF-HFP porous coating, achieving dual functionality of raindrop energy harvesting and radiative cooling. As illustrated in Fig. 1b, each triboelectric unit comprises a top Ag electrode, a bottom conductive fabric electrode, and an ePTFE electrification layer. The C-F groups of ePTFE confer superhydrophobicity (contact angle: 145°, Figure S1a), facilitating rapid droplet detachment and enhancing charge transfer^{32, 33}. Compared with glass/ceramic-based counterparts, this textile-engineered system harnesses two inherent merits: mechanical compliance and scalable

manufacturing compatibility, which are pivotal for outdoor applications such as building roofs and wearable devices with irregular shapes.

2.1. Design of EM-textile and regulation in raindrop energy harvesting

The working principle of the single EM-textile is explained in Fig. 2a, which contains six states^{14, 34, 35, 36}.

i) Before the droplet contacts the EM-textile, there is no charge transfer in the external circuit. Due to the difference in electronegativity between the materials, charges accumulate and reach saturation between the top surface of the ePTFE film (with triboelectric negative charges) and the conductive fabric (with induced positive charges) as raindrops continuously fall, and a capacitor C_p is formed. ii) As the droplet falls and contacts the ePTFE film surface, the negative charges on the ePTFE surface induce a separation of positive and negative charges within the raindrop. iii) When the raindrop continues to spread on the ePTFE film without contacting the Ag electrode, an electric double layer (EDL) is formed between the ePTFE surface and the raindrop. iv) When the spreading droplet touches the top Ag electrode, another EDL forms at the water/top electrode interface, and electrons flow rapidly from the top Ag electrode to the bottom conductive fabric electrode as the capacitor C_p charges C_2 . v) After the diffused droplet reaches the maximum area, there is a shrinkage in droplet area, thus a reduction of C_1 , which drives electrons to start to gradually flow back to the top Ag electrode while the capacitor C_2 begins to charge C_p . vi) Once the droplet rolls off the top electrode, the electricity generation cycle finishes. The entire process completes within 31.25 ms (Fig. 2b), demonstrating rapid energy conversion kinetics.

Besides, the hybrid EDL model is shown in Fig. 2c, which is the electric screening structure typically formed on the solid/liquid interface. The electrostatic field generated by electron transfer and chemisorbed ions on the solid surface gives rise to an electrostatically induced countercharge of equal magnitude on the bottom conductive fabric electrode. Consequently, when a subsequent raindrop contacts the negatively charged surface, electrostatic induction attracts the cationic species within the droplet to the interface, triggering EDL formation at the liquid-solid interface (Fig. 2c). And two EDLs are included in the EM-textile (the interface of ePTFE/raindrop and the interface of Ag/raindrop), as indicated by the two rectangles in Fig. 2d(i). The equivalent circuit of the EM-textile is presented in Fig. 2d, with a droplet serving as a switch. In the absence of a raindrop connecting the bottom conductive fabric and the Ag electrode, the switch is open (Fig. 2d(ii)). Under this open-circuit condition, the top ePTFE surface and the bottom conductive fabric electrode possess triboelectric negative and induced positive charges, respectively, thereby forming the capacitor C_p (Fig. 2a(i)). This open state confines all induced charges to the bottom electrode, generating a voltage difference on the order of hundreds of volts. Conversely, the circuit with the switch closed, corresponding to a waterdrop contacting the Ag electrode, is depicted in Fig. 2d(i). Simultaneously, the EDL at the ePTFE and raindrop interface forms the first capacitor (C_1), in which electron transfer occurs from a high-energy raindrop atom to a low-energy ePTFE atom when the interatomic distance enters the repulsive region (electron

cloud overlap), with electrostatic induction driving charge accumulation^{37, 38} (Fig. 2e), while the EDL at the raindrop and Ag electrode interface forms the second capacitor C_2 . At the nanoscale, impact pressure minimizes the separation between raindrops and ePTFE molecules, leading to a notably enhanced probability of charge transfer. This mechanism is illustrated by the evolution of their atomic-scale electron clouds before contact (Fig. 2e(i)), during contact (Fig. 2e(ii)), and after contact (Fig. 2e(iii)). COMSOL simulations corroborate this mechanism, tracking the evolution of surface potential across six representative positions as a droplet slides across the substrate (Fig. 2e(iv)). Therefore, when the raindrop contacts the Ag electrode, three capacitors (C_p , C_1 , and C_2) and two resistive elements (R_w and R) form a closed circuit (Fig. 2d(i)). The introduction of C_2 means that the stored electrical energy in C_p releases instantaneously, and then the stored electrical energy enters C_2 from C_p , triggering an electrical output, with electrons rapidly flowing from the top electrode to the bottom electrode until reaching the balanced voltage between C_p and C_2 , as described by the following equation:

$$V_{C_p} = \frac{Q_{C_p} \times d_p}{\epsilon_p \times S_p} = V_{C_2} = \frac{Q_{C_2} \times d_2}{\epsilon_2 \times S_2}$$

Where d_p and d_2 represent the thicknesses of C_p and C_2 , respectively; S_p and S_2 denote their corresponding areas; ϵ_p and ϵ_2 are the charge densities; and Q_{C_p} and Q_{C_2} are the stored charges in C_p and C_2 .

Because d_p exceeds d_2 at the raindrop/Ag electrode interface by several orders of magnitude, while $\epsilon_p \times S_p$ and $\epsilon_2 \times S_2$ are comparable in magnitude, Q_{C_2} significantly exceeds Q_{C_p} . This imbalance drives charge transfer from the bottom conductive fabric electrode to the Ag electrode during charging of C_2 by C_p . The transient charging process generates a pronounced current pulse. Consequently, per the relationship $I = Q/t$, the instantaneous current (I) reaches exceptionally high values at minimal discharge times. Upon contracting from the maximum spread area of the raindrop, the interfacial capacitance (C_1) is reduced, which in turn causes the voltage across C_2 to surpass that of C_p , reversing the charging direction such that C_2 charges C_p , producing a reverse current (Fig. 2a(v)).

To benchmark the enhancement conferred by the aforementioned switch structure, the EM-textile was compared against its analogous single-electrode triboelectric nanogenerators (S-TENG) and backside double-electrode (BD-TENG) counterparts under standardized conditions (51 μ L droplet, 20 cm release height, 50° tilt), the EM-textile achieves a 132 V open-circuit voltage and 74 μ A short-circuit current. This represents 15-fold and 6.7-fold enhancement over S-TENG and BD-TENG designs, respectively (Fig. 2f, Figure S2). Further investigation of spatial parameters (inclination angle, release height, and types of droplets) reveals the external factors of performance. As inclination increases from 30° to 50°, output voltage and current rise (Figure S3), are attributed to prolonged effective discharge time resulting from reduced droplet impact force and diffusion area. Beyond the optimum angle (> 50°), electrical performance declines concomitantly with reduced charge carrier participation in contact electrification,

caused by an excessively diminished droplet passage area and shortened charging reaction time. Regarding droplet dynamics, increased droplet height (10 cm to 50 cm) enhances charge transfer efficiency (Fig. 2g(i)) via greater impact velocity and expanded diffusion area. However, further height elevation reduces charge transfer due to droplet fragmentation upon impact, which diminishes effective solid-liquid interfacial contact^{14, 38}. Concerning aqueous composition, deionized (DI) water, rainwater, and tap water are comparatively assessed (Figure S4, Figure S5). While output voltage differences between DI water and rainwater were minimal, DI water exhibited the lowest output current due to its minimal ionic conductivity (inset in Figure S4). Mechanistically, droplets function as resistors in the EM-textile system; thus, the high electrical resistance of DI water limits current output. Conversely, elevated conductivity of tap water (inset in Figure S4) yields higher output currents (Figure S5). Rainwater demonstrates intermediate performance, since its ionic content and impurities may inhibit triboelectric charge transfer at the liquid-dielectric interface, reducing output charge/current relative to tap water¹⁴. Notably, EM-textile maintains robust rainwater harvesting efficiency, confirming precipitation energy collection viability. In addition, droplet volume affects the input energy of the system (Figure S6), exhibiting correlations with both diffusion area and transferred charge³⁵.

2.2. Energy calculation and electrical signal characteristics of multiple raindrops

To evaluate the peak power variation and energy supply capabilities of EM-textile, we systematically analyzed its output under controlled precipitation conditions (droplet height: 20 cm; tilt angle: 50°; raindrop volume: 51 μL), while sweeping load resistances from 100 Ω to 10 G Ω . The instantaneous power density was calculated by dividing the output power by the raindrop maximum diffusion area of 2.112 cm^2 . As Fig. 3a demonstrates, peak power density reaches 1.042 W/cm^2 at load resistance of 9.5 G Ω , corresponding to 2.2 W peak power. Meanwhile, accumulated energy per droplet reaches 1.27×10^{-4} J when load resistance approaches 9.5 G Ω (Fig. 3b). Notably, scaling droplet height from 10 to 30 cm produces an obvious energy increase (with the inclination remaining at 50°), consistent with the dynamic energy-height dependency of droplet (Figure S7a).

While EM-textile maintains identical intrinsic energy metrics, natural raindrops introduce inherent spatial-temporal randomness that must be considered in practical implementation, which challenges conventional energy harvesting schemes. To address this limitation and elucidate signal interference effects relevant to raindrop position and distribution density, electrical responses were investigated systematically³⁹, across both one common Ag electrode in the horizontal direction and three independent Ag electrodes in the horizontal direction along the direction perpendicular to the length of the electrode. For several droplets dropping on a common Ag electrode, the diagrammatic representation of the EM-textile with prolonged Ag electrode length is schematically shown in Figure S7b. Consistent signal characteristics are confirmed among the three droplets, and a certain degree of spatial-temporal separation is also exhibited. Similarly, vertical spacing tests show no significant signal overlap (Figure S8). To engineer practical applicability, a hierarchical EM-textile array was developed,

which comprised five functionally autonomous units, monolithically integrated on a $20 \times 20 \text{ cm}^2$ textile substrate (Fig. 3c). Each droplet harvesting unit was connected in parallel after rectification. The EM-textile demonstrated exceptional signal compatibility (Fig. 3d), exhibiting minimal peak overlap during simulated rainfall (370 droplets/m^2) within 0.17 s. The attenuation of signal interference enables adaptive multiplexing control by individual rectifiers, where only subcritical impact intervals between sequential raindrops on ePTFE surfaces elicit measurable crosstalk. This configuration preserves energy harvesting efficiency while significantly reducing system complexity, achieving an optimal balance between cost-effectiveness and scalability through shared electrode array configuration.

Empirical evaluations substantiate the superior energy conversion characteristics of the system. As shown in Fig. 3e, the EM-textile featuring only one operational Ag electrode in the circuit is employed to individually charge $0.1 \text{ }\mu\text{F}$, $0.22 \text{ }\mu\text{F}$, and $1 \text{ }\mu\text{F}$ capacitors to 2 V within approximately 2.4 s, 6.4 s, and 106.7 s. The instantaneous illumination of a 44-LED “TENG” array (Fig. 3e) upon single droplet impact directly verifies the high-efficiency mechanoelectrical transduction pathway. Notably, the array configuration featuring five operational Ag electrodes significantly accelerates charging kinetics by 1.6–2.2 times over a configuration with a single electrode, reaching 2 V in 1.4 s, 4 s, and 48.8 s for identical capacitors (Fig. 3f). Furthermore, the system successfully powered a timer by charging a $4.7 \text{ }\mu\text{F}$ capacitor to 2 V within 71 s, validating practical micro-energy supply capabilities for wearable electronics. These findings systematically progress from static device characterization (LED activation) through dynamic storage evaluation (capacitor charging) to system-level application demonstration (timer operation), comprehensively validating the potential for practical applications in powering small electronic devices.

2.3. Radiative cooling mechanism and performance of the EM-textile

The engineered radiative cooling functionality (Fig. 4a(i)) of the EM-textile originates from an elaborately designed multiscale photonic structure (Fig. 4b) that synergistically integrates with its energy harvesting framework. As illustrated in Fig. 4a(ii)-(v), the thin ePTFE layer ($40\text{--}60 \text{ }\mu\text{m}$ in thickness) and the composite fabric coated with the PVDF-HFP porous polymer are applied in the EM-textile, which contains nano-pores and micro-pores with diameters ranging from $0.2 \text{ }\mu\text{m}$ to $10.8 \text{ }\mu\text{m}$, as well as ePTFE nanofibers that are several micrometers in length and less than $0.2 \text{ }\mu\text{m}$ in width (Fig. 4a(ii), (iv)). The ePTFE nanofibers with $0.1 \text{ }\mu\text{m}$ in size strongly reflect ultraviolet (UV) light before it reaches the PVDF-HFP-coated fabric. The layered porous PVDF-HFP structure with dual-scale-pores ranging from 0.2 to $10.8 \text{ }\mu\text{m}$ (Fig. 4a(iii), (v), Figure S9), formed through phase separation techniques²⁶ (Fig. 4a, Figure S10). Such dual-scale porous structures leverage collective Mie resonances to generate scattering peaks that continuously span the visible-to-near-infrared (VIS-NIR) spectrum with high efficiency (Fig. 4b).

The EM-textile achieves exemplary passive daytime radiative cooling (PDRC) performance through strategic material-structure synergy, where PVDF-HFP and ePTFE collaboratively address the dual-spectrum requirements of solar reflection and mid-infrared (MIR) emission. Both polymers exhibit

negligible extinction coefficients (Figure S11) across the solar spectrum, effectively decoupling photon absorption while permitting near-perfect solar reflectivity (R_{solar}) of 95.2% (Fig. 4c). This optical performance is complemented by engineered dipole-phonon resonances in PVDF-HFP, generating extinction peaks (Figure S11b) within the atmospheric transparency window (ATSW, 8–13 μm), which collectively deliver MIR emissions ($\epsilon_{\text{MIR}} = 94\%-99\%$). Although the Ag electrode exhibits suboptimal radiative characteristics ($\epsilon_{\text{MIR}} = 51.6\%$, $R_{\text{solar}} = 76.2\%$, Figure S12), as evidenced during indoor simulated solar testing (12.5 $^{\circ}\text{C}$ higher than pristine EM-textile, Figure S13), its limited surface coverage (10%, Fig. 4c inset) maintain the high MIR emissivity and solar reflectivity ($\epsilon_{\text{MIR}} = 94.0\%$, $R_{\text{solar}} = 93.3\%$) of the EM-textile, while incurring minor optical trade-offs ($\Delta R_{\text{solar}} = -1.9\%$ versus pristine EM-textile) is an acceptable trade-off given its essential triboelectric functionality.

Field tests under real-world subtropical conditions (Suzhou, China, 31° 16' 21.86" N, 120° 43' 35.52" E) quantified the EM-textile's all-day radiative cooling capabilities through continuous 24-hour thermal profiling (Fig. 4d-e and Figure S14). To ensure the accuracy and uniformity of the thermal measurements, the temperature of each fabric sample was monitored using two K-type thermocouples attached to a copper plate (Figure S14 and Figure S15). As shown in Figure S14, the temperature at the center of the sample was lower than at the edge, indicating that the sample's temperature was effectively reduced compared to the aluminum foil and silver mylar. Specifically, the EM-textile maintained a temperature lower than the ambient temperature over a continuous 24-hour measurement period (Fig. 4d-e, Figure S14, Figure S16). During the daytime, it achieved a subambient cooling effect of 4–5 $^{\circ}\text{C}$ lower than the ambient temperature while generating an average cooling power of 66.4 W/m^2 (Fig. 4d). At nighttime, the minimum temperature difference was approximately 4–5 $^{\circ}\text{C}$ with an average cooling power of 66.1 W/m^2 (Fig. 4e). These results demonstrate the EM-textile's stable and remarkable cooling performance both during the day and at night. This all-day operational consistency demonstrates viability for scalable deployment in urban heat mitigation scenarios, including building rooftops and public infrastructure.

2.4. The potential for energy-saving

The systemic energy advantage of EM-textile emerges from its dual-function integration, where radiative cooling and droplet energy harvesting operate synergistically to enhance building energy management efficacy. As schematized in Fig. 5a, the engineered EM-textile combines high solar reflectivity, superhydrophobicity, all-weather operation, and superior comprehensive performance, and can be applied to outdoor multi-scenario applications.

To validate the EM-textile's dual-functional implementation in building energy systems, we designed a synergistic roof architecture comprising: a rainwater storage module for precipitation collection, a programmable droplet generation array for controlled hydraulic energy release, and a 16-unit EM-textile matrix for concurrent thermal regulation and power conversion (Fig. 5b and Figure S17). The 16-unit EM-textile could power an LED logo through rain-induced triboelectric generation while maintaining 2 $^{\circ}\text{C}$ lower interior temperatures than conventional roofs in the midday of a clear day (Fig. 5c). To assess the

EM-textile's cross-platform adaptability beyond architectural applications, we conducted automotive cooling trials in summer conditions (Figure S18). As shown in the corresponding thermal image, EM-textile cladding achieved an obvious cooling effect with a large temperature difference of 15 °C. These results highlight its potential for commercial use in a variety of outdoor scenarios and facilities, such as building surfaces, outdoor shading products, and outdoor bus shelters (Fig. 5a, Figure S19).

Moreover, an energy consumption and energy harvesting simulation of a mid-level apartment building⁴⁰(as the showed model details in Note 5 and Table S1 in supplement) was conducted to assess the energy saving and droplet energy recovery performance on a worldwide scale (Fig. 5d) by applying the EM-textile as the external envelope material on the walls and roof based on the simulation and calculation of Energyplus, as well as annual precipitation data in the year 2021⁴¹. In tropical and subtropical countries like Singapore, the annual energy savings of 8.74 GJ in cooling. Besides, the energy of 7.61 kJ recovered from raindrops are potential for powering sensors and standby electronic devices.

To evaluate global energy-saving potential, EM-textile was modeled as an external envelope material for walls and roofs. Analysis of HVAC energy consumption reveals maximal benefits in tropical and subtropical regions (Fig. 5d and Fig. 5e), where annual energy savings can peak at 15 GJ, alongside droplet energy recovery reaching as high as 11.5 kJ. For practical application, the woven architecture provides mechanical compliance, including scalability, bendability, and stretchability (Figure S20, Figure S21), enabling seamless integration into commercial textile products such as car covers and tents^{42, 43}.

3. Conclusions

In summary, this work introduces a textile-engineered energy-managing (EM-textile) platform that redefines outdoor energy interfaces by synergistically integrating droplet-based electricity harvesting with passive daytime radiative cooling (PDRC). Utilizing a nanostructured PVDF-HFP/ePTFE composite, the textile achieves an exceptional raindrop-energy peak power density of 1.042 W/cm², sufficient to illuminate 44 LEDs from a single droplet, alongside high solar reflectivity (93.3%) and mid-infrared emissivity (94.0%). This dual-functional architecture enables simultaneous power generation and sub-ambient cooling (4–5 °C drop under 965 W/m² irradiance) without parasitic energy consumption, successfully overcoming the trade-offs of traditional single-purpose energy devices. Field validations demonstrate versatile real-world applicability: building integrations achieve temperature reductions of 4 °C (exterior) and 2 °C (interior) while autonomously powering electronics, and vehicle claddings achieve up to a 15 °C surface temperature drop. Global energy modeling highlights significant carbon-mitigation potential, projecting annual building savings of 15 GJ in cooling energy and 11.5 kJ in harvested droplet energy in tropical regions. Supported by its mechanically compliant, UV-stable woven design, the EM-textile provides a scalable, industrial-compatible pathway toward climate-resilient urban infrastructure, net-zero smart buildings, and next-generation wearable technologies.

4. Experimental Section

Fabrication of textile-based EM-textile devices: The PVDF-HFP porous coating and ePTFE nanofiber film, fabricated on the knitted fabric substrate that was custom-woven in our laboratory⁴⁴, acted as the triboelectric layer and radiative cooling layer, respectively. The fabric substrate was immersed in a PVDF-HFP/acetone/water solution (1:8:1 mass ratio) at 25 °C for 5 min, subsequently oven-dried at 60 °C for 1 hour. The sample was then thermally laminated with an ePTFE nanofiber film at 120 °C. Finally, brush-deposited conductive silver paste electrodes were formed on the ePTFE surface, followed by room-temperature drying to yield the multifunctional EM-textile.

Morphology and Wettability Characterization

Sample morphology was characterized by scanning electron microscopy (Regulus 8100, Hitachi). Surface wettability was evaluated via contact angle measurements using a SmartDrop analyzer (FEMTOBIOMED), quantifying the hydrophobic properties of polymer films.

Triboelectric Output Performance of the EM-textile

A programmable electrometer (Keithley, Model 6514), a DMM7510 multimeter, and an oscilloscope (SR570) were employed to measure the open-circuit voltage, short-circuit current, and short-circuit charge transfer of the fabric. Single-electrode designs (S-TENG) were grounded in single-electrode mode, while back double-electrode configurations (BD-TENG) employed two isolated electrodes. The EM-textile was interfaced with both the back electrode and screen-printed Ag electrode.

Test of charging ability and driving ability of textile-based EM-textile array

As shown in Fig. 3c, a 40 cm×40 cm×40 cm acrylic chamber with a top hole was used to simulate irregular rainfall conditions. The EM-textile was mounted on an ePTFE plate and placed inside the acrylic chamber, with the ePTFE plate adjusted to the desired tilt angle. The drip control tube was inserted into the top hole to simulate raindrops. Both a single EM-textile unit and five EM-textile units connected in parallel were used to charge capacitors with varying capacitance values, while a multimeter (DMM7510) monitored the voltage across the capacitors in real time. During the drive capability test, a 4.7 μF capacitor was charged to 2 V using five EM-textile units, and the circuit connection mode was then altered to drive a timer. Throughout the testing process, the multimeter DMM7510 continuously recorded the voltage changes across the capacitor.

Optical characterization

Sample optical properties were characterized across ultraviolet-near-infrared (UV-NIR; 0.25–2.5 μm) and mid-infrared (MIR; 2.5–20 μm) spectral regimes. UV-NIR reflectance was quantified using a Shimadzu UV-3600 spectrophotometer with an integrating sphere, referenced against an ePTFE standard plate. Mid-infrared emissivity was measured via Fourier transform infrared spectroscopy (Thermo Fisher Nicolet IS50) with gold-coated integrating spheres. UV-NIR transmission spectra were acquired using the same Shimadzu system configured for direct detection.

Refractive index measurements

As shown in Figure S11, refractive index measurements of ePTFE and PVDF-HFP films were taken by an IR-VASE ellipsometer (J. A. Woollam, USA).

Declarations

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Data Availability Statement

All data needed to evaluate the conclusions in the paper are present in the paper and the Supporting Information.

References

1. Yan J (2026) Urban Energy Transformation Through Integrated Systems. *Nat Energy* 11:16–17
2. Chu S, Majumdar A (2012) Opportunities and Challenges for a Sustainable Energy Future. *Nature* 488:294–303
3. Zhao J, Li FX, Zhang QW (2024) Impacts of Renewable Energy Resources on the Weather Vulnerability of Power Systems. *Nat Energy* 9:1407–1414
4. Quagraine KA, Lynas M, Ellis EC (2026) As We Breach 1.5 °C, We Must Replace Temperature Limits with Clean-Energy Targets. *Nature* 649:1103–1106
5. Sinsel SR, Riemke RL, Hoffmann VH (2020) Challenges and Solution Technologies for the Integration of Variable Renewable Energy Sources—a Review. *Renewable Energy* 145:2271–2285
6. Li Z, Yang D, Zhang Z et al (2022) A Droplet-Based Electricity Generator for Large-Scale Raindrop Energy Harvesting. *Nano Energy* 100:107443
7. Xu L, Xu L, Luo J et al (2020) Hybrid All-in-One Power Source Based on High-Performance Spherical Triboelectric Nanogenerators for Harvesting Environmental Energy. *Adv Energy Mater* 10:2001669

8. Zhang Y, Liu J, Zhang J et al (2024) A Flexible Droplet-Based Triboelectric-Electromagnetic Hybrid Generator for Raindrop Energy Harvesting. *Nano Energy* 121:109253
9. Xia P, Sun H, Guo H et al (2024) Luminescent Solar Concentrator with Advanced Structure for Reabsorption Loss Suppression and Synergistic Energy Harvesting. *Adv Funct Mater* 34:2401121
10. Zhou L, Zhang D, Ji X et al (2024) A Superhydrophobic Droplet Triboelectric Nanogenerator Inspired by Water Strider for Self-Powered Smart Greenhouse. *Nano Energy* 129:109985
11. Zhang Q, Liang Q, Liao Q et al (2018) An Amphiphobic Hydraulic Triboelectric Nanogenerator for a Self-Cleaning and Self-Charging Power System. *Adv Funct Mater* 28:1803117
12. Wang Y, Gao S, Xu W et al (2020) Nanogenerators with Superwetting Surfaces for Harvesting Water/Liquid Energy. *Adv Funct Mater* 30:1908252
13. Xu X, Li P, Ding Y et al (2022) Droplet Energy Harvesting Panel *Energy & Environ Science* 15:2916–2926
14. Ye C, Liu D, Chen P et al (2023) An Integrated Solar Panel with a Triboelectric Nanogenerator Array for Synergistic Harvesting of Raindrop and Solar Energy. *Adv Mater* 35:2209713
15. Zhang Q, Jiang C, Li X et al (2021) Highly Efficient Raindrop Energy-Based Triboelectric Nanogenerator for Self-Powered Intelligent Greenhouse. *ACS Nano* 15:12314–12323
16. Tang Y, Fu H, Xu B (2024) Advanced Design of Triboelectric Nanogenerators for Future Eco-Smart Cities. *Adv Compos Hybrid Mater* 7:102
17. Sun Q, Wang D, Li Y et al (2019) Surface Charge Printing for Programmed Droplet Transport. *Nat Mater* 18:936–941
18. Xu W, Zheng H, Liu Y et al (2020) A Droplet-Based Electricity Generator with High Instantaneous Power Density. *Nature* 578:392–396
19. Yuan J, Yang X, Zheng D et al (2023) Perovskite Quantum Dot-Based Tandem Triboelectric-Solar Cell for Boosting the Efficiency and Rain Energy Harvesting. *Nano Energy* 110:108341
20. Xie L, Yin L, Liu Y et al (2022) Interface Engineering for Efficient Raindrop Solar Cell. *ACS Nano* 16:5292–5302
21. Wang L, Wang Y, Wang H et al (2020) Carbon Dot-Based Composite Films for Simultaneously Harvesting Raindrop Energy and Boosting Solar Energy Conversion Efficiency in Hybrid Cells. *ACS Nano* 14:10359–10369
22. Kim B, Song JY, Kim DY et al (2022) All-Aerosol-Sprayed High-Performance Transparent Triboelectric Nanogenerator with Embedded Charge-Storage Layer for Self-Powered Invisible Security IoT System and Raindrop-Solar Hybrid Energy Harvester. *Nano Energy* 104:107878
23. Li X, Luo J, Han K et al (2022) Stimulation of Ambient Energy Generated Electric Field on Crop Plant Growth. *Nat Food* 3:133–142
24. Yang Y, Zhang G, Rong L (2024) Temperature Adaptive Passive Daytime Radiative Cooling: The Impact of Their Essential Properties on Energy Performance of Different Building Types. *Energy Build* 325:114955

25. Smith G, Gentle A (2017) Radiative Cooling: Energy Savings from the Sky. *Nat Energy* 2:17142
26. Liu Y, Lei D (2025) Painting Humid Cities Cool. *Nat Energy* 10:1293–1294
27. Yao P, Chen Z, Liu T et al (2022) Spider-Silk-Inspired Nanocomposite Polymers for Durable Daytime Radiative Cooling. *Adv Mater* 34:2208236
28. Fu Y, Ma X, Zhang X-W et al (2025) Photoluminescent Radiative Cooling for Aesthetic and Urban Comfort. *Nat Sustain* 8:1328–1339
29. Parliament E (2023) Amendments Adopted by the European Parliament on 14 March 2023 on the Proposal for a Directive of the European Parliament and of the Council on the Energy Performance of Buildings (recast). https://www.europarl.europa.eu/doceo/document/TA-9-2023-0068_EN.html#title2
30. Bruck A, Diaz Ruano S, Auer H (2022) Values and Implications of Building Envelope Retrofitting for Residential Positive Energy Districts. *Energy Build* 275:112493
31. Lee G, Kang H, Yun J et al (2024) Integrated Triboelectric Nanogenerator and Radiative Cooler for All-Weather Transparent Glass Surfaces. *Nat Commun* 15:6537
32. Meng H, Zhang J, Zhu R et al (2024) Elevating Outputs of Droplet Triboelectric Nanogenerator through Strategic Surface Molecular Engineering. *ACS Energy Lett* 9:2670–2676
33. Kong Z, Boahen EK, Kim DJ et al (2024) Ultrafast Underwater Self-Healing Piezo-Ionic Elastomer via Dynamic Hydrophobic-Hydrolytic Domains. *Nat Commun* 15:2129
34. Liu X, Yu A, Qin A et al (2019) Highly Integrated Triboelectric Nanogenerator for Efficiently Harvesting Raindrop Energy. *Adv Mater Technol* 4:1900608
35. Liu D, Yang P, Gao Y et al (2024) A Dual-Mode Triboelectric Nanogenerator for Efficiently Harvesting Droplet Energy. *Small* 20:2400698
36. Meng J, Zhang L, Liu H et al (2024) A New Single-Electrode Generator for Water Droplet Energy Harvesting with a 3 mA Current Output. *Adv Energy Mater* 14:2303298
37. Li LX, Li XM, Deng W et al (2023) Sparking Potential over 1200 V by a Falling Water Droplet. *Sci Adv* 9:eadi2993
38. Zheng Y, Liu T, Wu JP et al (2022) Energy Conversion Analysis of Multilayered Triboelectric Nanogenerators for Synergistic Rain and Solar Energy Harvesting. *Adv Mater* 34:28
39. Hodson MC (1986) Raindrop Size Distribution. *J Appl Meteorol Climatology* 25:1070–1074
40. Deru MEA, US Department of Energy Commercial Reference Building Models of the National Building Stock-Technical Report (2010) (Tech. Rep. NREL/TP-5500-46861, National Renewable Energy Laboratory, February 2011; <https://docs.nrl.gov/docs/fy11osti/46861.pdf>). [the easiest access to this source is via the URL]
41. Hersbach H, Bell B, Berrisford P et al ERA5 Hourly Data on Single Levels from 1940 to Present, in *Copernicus Climate Change Service (C3S) Climate Data Store (CDS)*. (10.24381/cds.adbb2d47). [the easiest access to this source is via the URL]

42. Cai C, Wu X, Cheng F et al (2024) Cellulose Metamaterials with Hetero-Profiled Topology via Structure Rearrangement during Ball Milling for Daytime Radiative Cooling. *Adv Funct Mater* 34:2405903

43. Liu J, Wei Y, Zhong Y et al (2024) Hierarchical Gradient Structural Porous Metamaterial with Selective Spectral Response for Daytime Passive Radiative Cooling. *Adv Funct Mater* 34:2406393

44. Wang Y, Wang Z, Sun L et al (2025) Scale Manufacturing of Braided Coaxial Triboelectric Yarns for Flexible Wearable Smart Electronics for Energy Harvesting, Motion Sensing and Human-Computer Interaction. *Chem Eng J* 520:165881

Figures

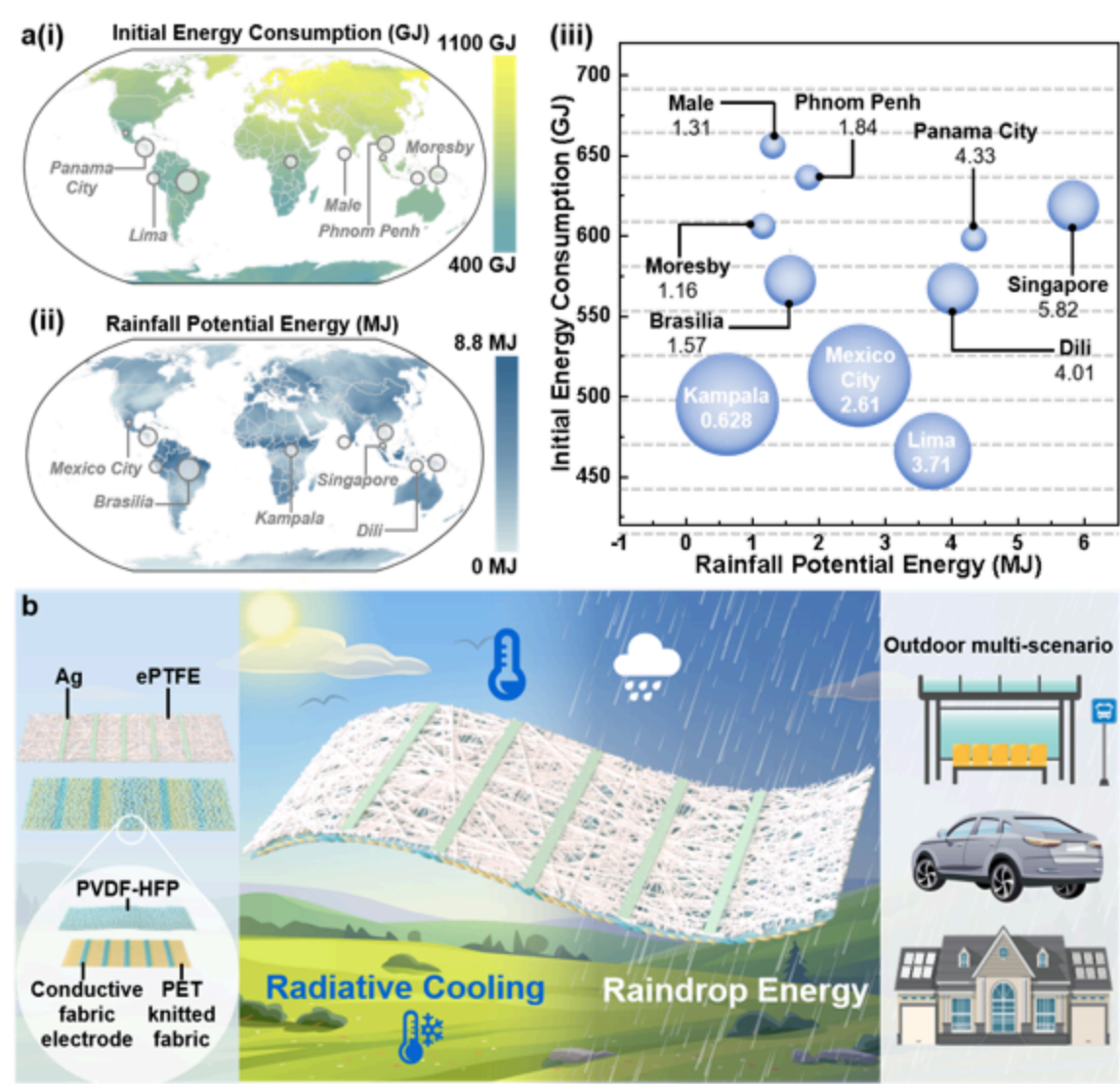


Figure 1

Concept of the textile-based raindrop triboelectric nanogenerator and passive daytime radiative cooling system as a sustainable energy device. (a) (i) The global annual mean distribution of energy

consumption for building cooling and (ii) potential energy contained in global rainfall. (iii) Estimated annual rainfall potential energy and building cooling energy consumption for 10 representative tropical cities with high irradiance or rainfall. (b) Schematic of EM-textile system that can reduce energy consumption on sunny days and harvest electrical energy from rainfall on rainy days.

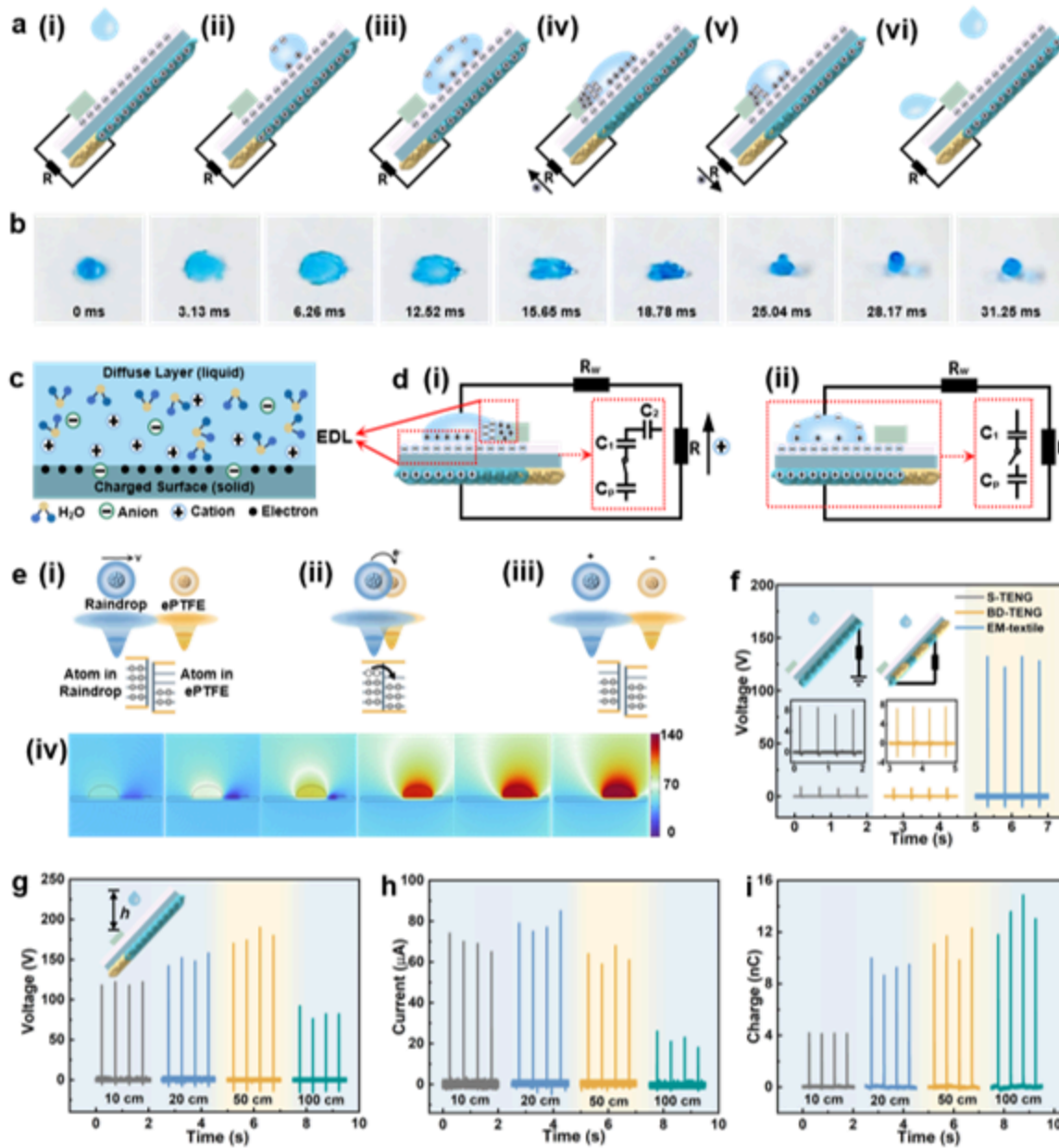


Figure 2

Design and electrical performance control of EM-textile. (a) Mechanism of raindrop energy collecting part of the EM-textile, including schematic of the electricity generation process during the droplet flow sequence. (b) Snapshots showing the spreading process of one droplet on the EM-textile surface from dripping onto the surface to shrinking into clusters. The droplet with a diameter of 4.6 mm drops from a height of 20 cm, and the slope of the surface is 50°. (c) Schematic of the hybrid electric double layer (EDL) model for explaining the liquid-solid triboelectrification. (d) Equivalent working circuit diagram of

EM-textile, including schematic of charge distribution in the device after (i) and before (ii) the spreading raindrop touches the top Ag electrode, and the spreading water droplet was treated as a resistor, R_w . (e) Schematic diagram of contact electrification between solid and liquid materials and the (iv) COMSOL simulation of the triboelectric charging process of the sliding raindrop. (f) The output voltage of EM-textile compared with S-TENG and BD-TENG. (g) Comparison of peak voltage, (h) short-circuit current, and (i) quantity of electric charge according to the raindrop height.

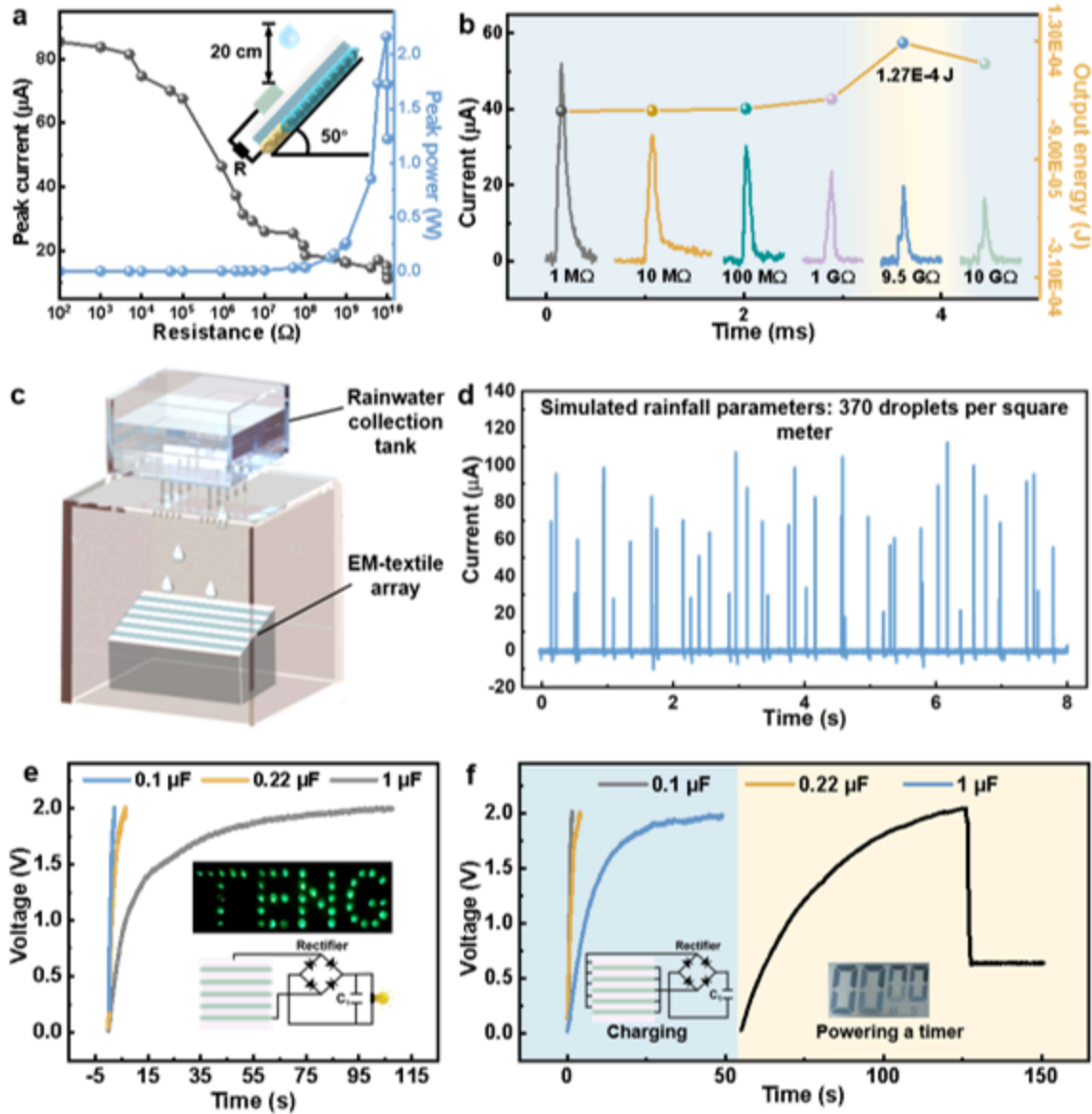


Figure 3

Quantification of raindrop energy harvesting and multi-droplet electrical output characteristics in EM-textile arrays. (a) Relationship between the peak current/the corresponding peak power and the load resistance. (b) The output energy of a single water drop falling from a height of 20 cm related to different external resistors. (c) Schematic illustration of the arrayed device to simulate actual rainfall. (d) Composite current signals of the raindrops dropping on the surface of the EM-textile during the

simulated rainfall (370 droplets/m²). (e) Demonstration of charging voltages on different capacitors charged by an EM-textile featuring only one operational Ag electrode in the circuit and lighting 44 LED bulbs, and (f) charging voltage on different capacitors charged by the array configuration featuring five operational Ag electrodes and demonstrations of continuously powering a timer.

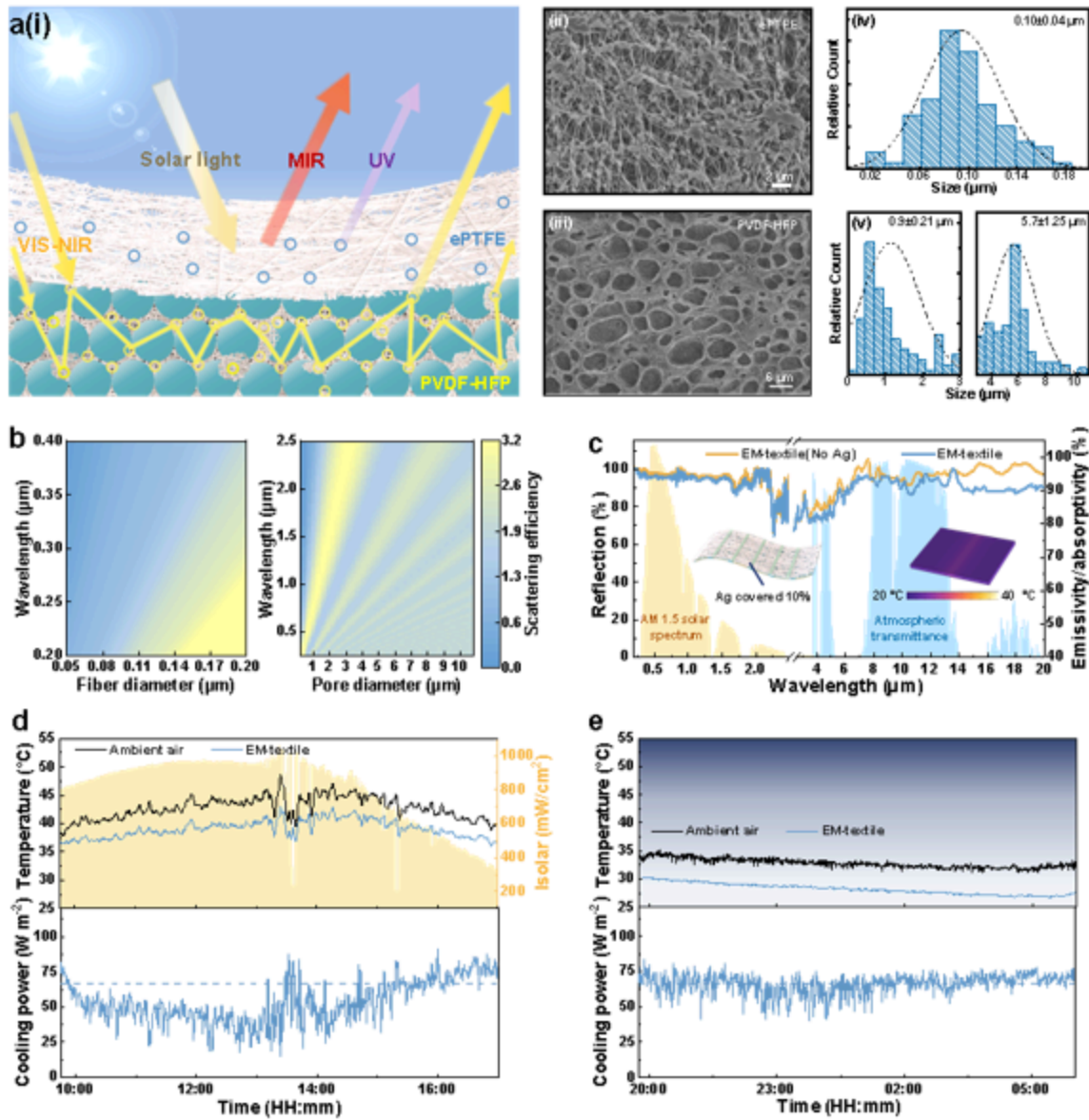


Figure 4

Engineered hierarchically porous cooling EM-textile and cooling performance characterization. (a) (i) Schematic of the EM-textile for daytime radiative cooling. The blue and yellow solid frames highlight the two-level hierarchical structure responding to the UV, VIS-NIR, and MIR bands, respectively. (ii) SEM images of the ePTFE in blue frames and (iii) the PVDF-HFP in yellow frames. The size distribution of (iv) ePTFE nanofibers and (v) the porous PVDF-HFP system. (b) Simulated scattering efficiency of different-sized ePTFE nanofibers (0.05-0.18 μm) encapsulated in EM-textile and the porous PVDF-HFP system (0.2-10.8 μm). (c) Measured reflectivity and emissivity spectra of the EM-textile (0.2 to 20 μm). (d)

Continuous temperature measurement of the subambient cooling performance test in Suzhou, China (31° 16' 21.86" N, 120° 43' 35.52" E, 29 and 30 July 2024), and calculated net cooling power of the EM-textile versus ambient temperature by using different heat convection coefficients during the daytime and (e) at night.

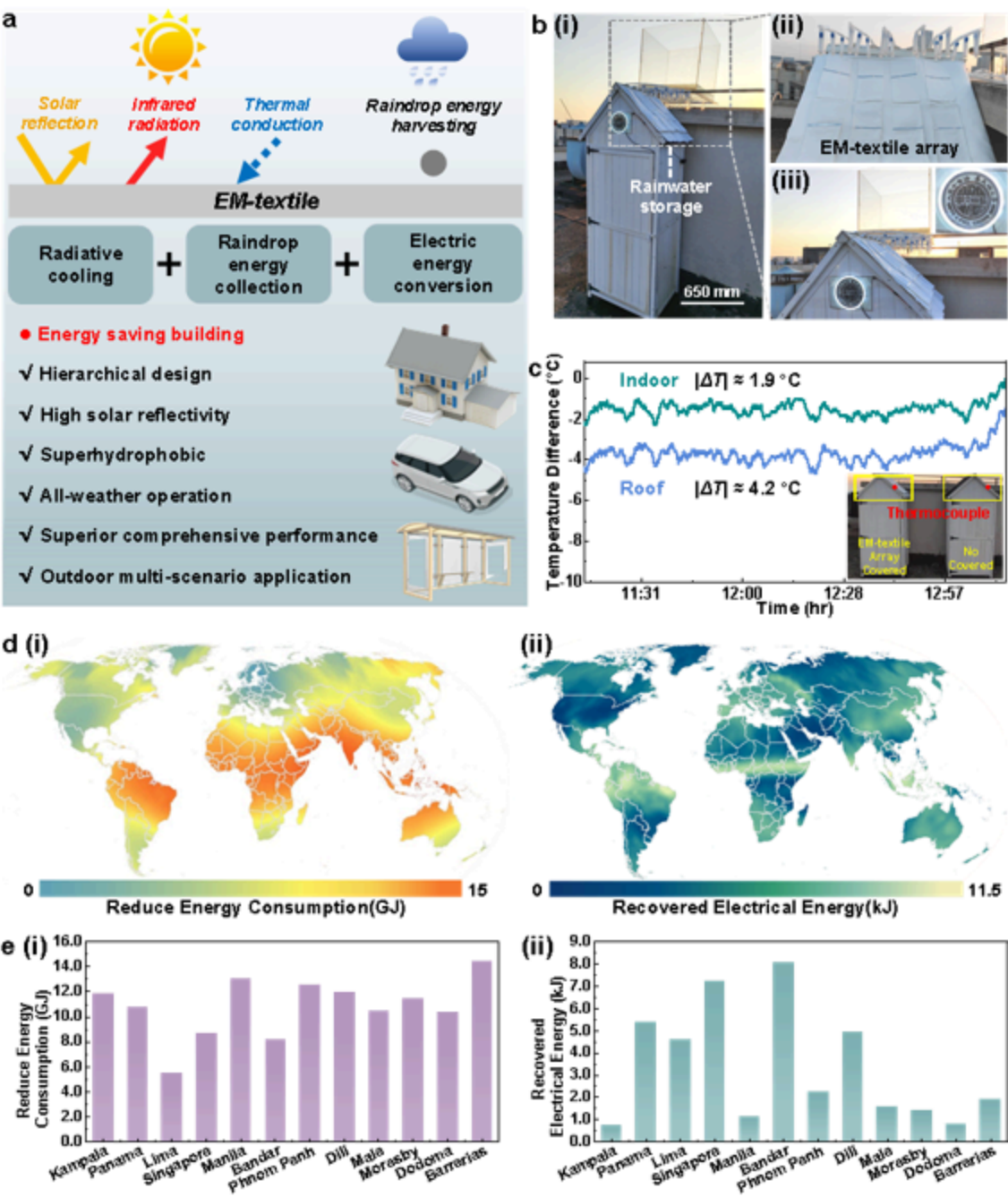


Figure 5

Application and energy saving estimation of EM-textile. (a) Proposed mechanism of EM-textile for dual functionality of raindrop energy harvesting and radiative cooling. (b) Photos of the model log cabin, with white EM-textile roofing materials applied to the roof. A schematic diagram of i) the synergistic roof architecture and ii) the 16-unit EM-textile matrix for concurrent thermal regulation and raindrop energy

conversion. iii) Photos of the LED logo being powered through rain-induced triboelectric generation. (c) Differences in temperatures compared to the ambient temperature in the roof and indoor air for the two model houses. (d) Simulation of i) energy-saving performance and ii) energy recovery on a global scale. (e) Estimated annual i) energy-saving of building cooling and ii) rainfall energy recovery for 12 representative tropical cities with high irradiance or rainfall.

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